Correlation of pick-off annihilation cross section and the collisional cross section for Ps-atom/molecule collisions

Ken Wada and Toshio Hyodo
Institute of Materials Structure Science, High Energy Accelerator Organization (KEK),
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

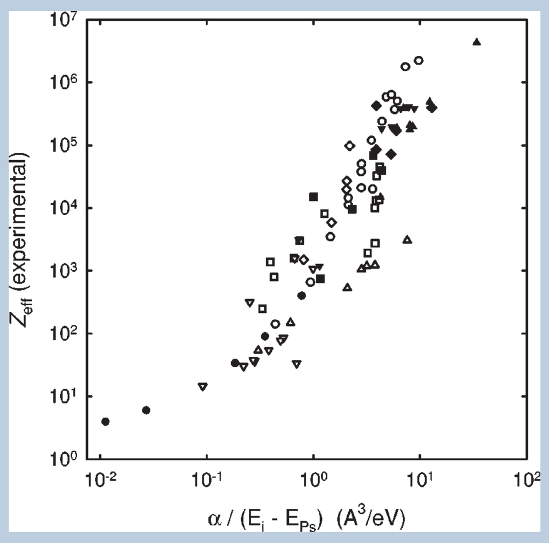
Positronium quenching through its collisions with gaseous atoms and molecules is discussed. It is found that the values of the normalized pick-off quenching parameter, ${}^1Z_{\rm eff}$, at room temperature are practically proportional to the geometric collisional cross-sections estimated from the radius of the positronium and those of the atoms and molecules derived from the viscosity. This suggests that the probabilities of the pick-off quenching of the thermalized positronium per collision with various atoms and molecules are almost constant.

Positron annihilation in gases

The annihilation rate of the positron in gaseous media, λ_+, is proportional to the density of the gas, unless the density is too high or the temperature is too low. It is convenient to normalize it to the density of the gas, n. If we further normalize it by the Dirac annhilation rate for unit electron density at the positron, $\pi r_0{}^2 c$, a dimensionless parameter is introduced:

$$Z_{\rm eff} = \frac{\lambda_+}{\pi r_0{}^2 c\, n}\,. \qquad (1)$$

The experimental values of $Z_{\rm eff}$ spread widely across seven orders of magnitude. Using detailed experimental and theoretical works from the last two decades, especially those focusing on the energy dependence, most of the values has been explained well with both the long- and short-range correlation effects and the formation of temporary positron-molecule bound states due to vibrational Feshbach resonances [1].



cited from ref. [2].

Ps quenching in gases

Among positronium (Ps) atoms, para-Ps (p-Ps, spin-singlet) self-annihilates into 2γ at a rate of $1/125\,{\rm ps}^{-1}$ while ortho-Ps (o-Ps, spin-triplet) self-annihilates into 3γ at $1/142\,{\rm ns}^{-1}$ in vacuum. The annihilation rate of o-Ps measured in a gaseous medium, $\lambda_{\rm total}$, is greater than the self-annihilation rate, $\lambda_{3\gamma}$, due to collisional quenchings where

$$\lambda_{\rm total} = \lambda_{3\gamma} + \lambda_{\rm quench}\,. \qquad (2)$$

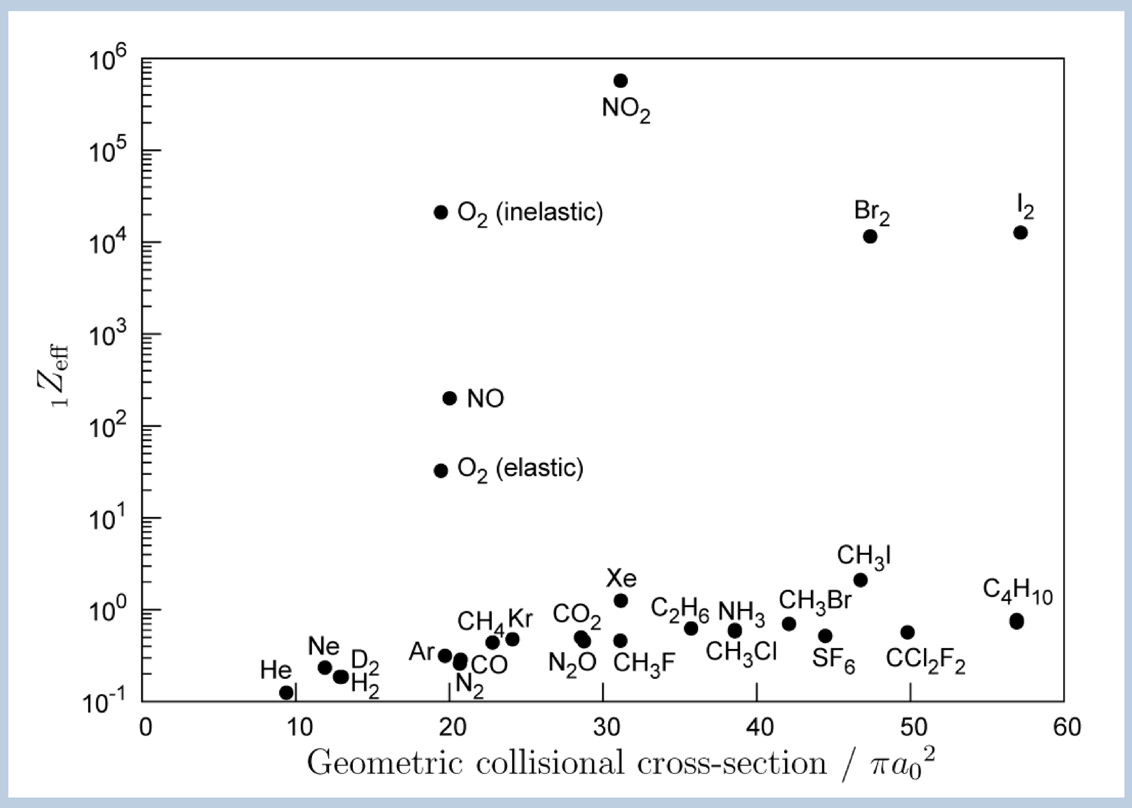
In the case of pick-off quenching, the positron of the o-Ps annihilates with the electron in the molecules which is in a spin-singlet state relative to the positron. The pick-off quenching rate, $\lambda_{\rm pick\text{-}off}$, is conventionally normalized to the gas density, n, and the Dirac rate, $4\pi r_0{}^2 c$, for unit spin-singlet electron density, *viz*,

$${}^1Z_{\rm eff} = \frac{\lambda_{\rm pick\text{-}off}}{4\pi r_0{}^2 c\, n}\,. \qquad (3)$$

There are other quenching processes in addition to the pick-off. We introduce a parameter including all quenching processes with the "subscript" 1 as

$${}_1Z_{\rm eff} = \frac{\lambda_{\rm quench}}{4\pi r_0{}^2 c\, n}\,, \qquad (4)$$

Experimental values of ${}_1Z_{\rm eff}$



Experimental values are cited from refs.[3-6] and others. Geometric collisional cross-section, $\sigma_{\rm geom}$, is $\pi(a_0 + d/2)^2$. Here a_0 is the Bohr radius and d is the diameter of the molecule estimated from its viscosity, η, by the equation $\pi(d/2)^2 = M\overline{v}/8\sqrt{2}\eta$. M and $\overline{v}$ are the mass and the averaged speed of the molecule, respectively.

Quenching channels

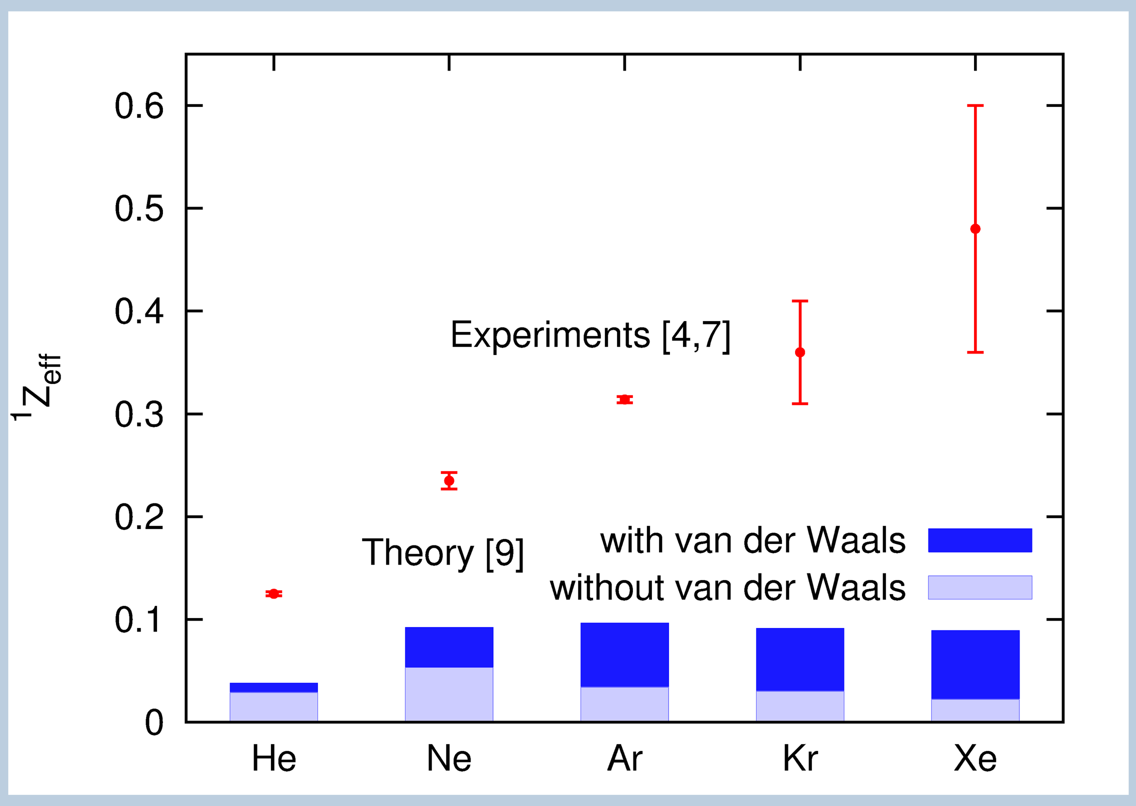
Pick-off quenching: All gases.

Spin conversion quenching through electron exchange: O_2 and NO [3,5]. It takes place only when either the initial or final state of the target is non-singlet.

Chemical or attachment quenching: NO_2, Br_2, and I_2 [3]. The o-Ps is first bound to or be in a resonant state with these molecules.

Spin conversion quenching through spin-orbit interaction: Kr (${}_1Z_{\rm eff} = 0.478(3)$), Xe (1.26(1)), and probably CH_3I (2.1(2)) [4,6]. Decomposition required to isolate $\lambda_{\rm pick\text{-}off}$ only.

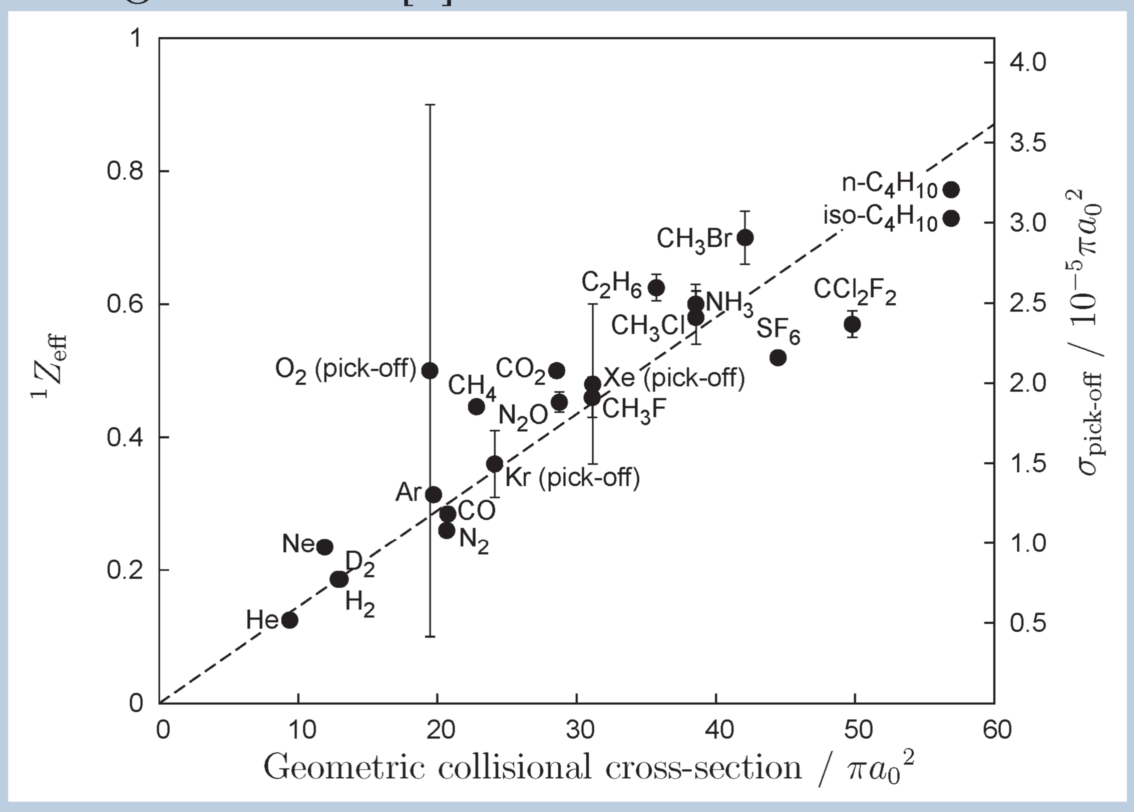
Theoretical calculation of ${}^1Z_{\rm eff}$



There are only a few calculations for He [8], one for Ne, Ar, Kr, and Xe [9], and none for any others. Inclusion of the enhancement due to many-body effects, as was done for He to explain experimental result [11], may resolve the discrepancies between calculations and experiments.

Pick-off quenching

The values of ${}^1Z_{\rm eff}$ ($\equiv {}_1Z_{\rm eff}$(pick-off)) for the atoms and molecules are shown below against $\sigma_{\rm geom}$ in a linear scale. The ${}^1Z_{\rm eff}$ values for O_2 was obtained by decomposing with the age-momentum correlation (AMOC) technique [10], and those for Kr and Xe with an effective use of a magnetic field [7].



The right vertical axis indicates the pick-off quenching cross-section, $\sigma_{\rm pick\text{-}off}$, which is related to ${}^1Z_{\rm eff}$ as $\sigma_{\rm pick\text{-}off} = 4\pi r_0{}^2 c\, {}^1Z_{\rm eff}/v_{\rm rel}$. Here, $v_{\rm rel}$ is the relative speed of the centers of mass of the molecule and the Ps.

The experimental values of ${}^1Z_{\rm eff}$ are roughly proportional to the geometric collisional cross-section. If we take $\sigma_{\rm geom}$ for the real scattering cross-section, the linear dependence of the plots indicates that the pick-off quenching probability per collision, P, does not vary much among those atoms and molecules, namely, $P \sim \sigma_{\rm pick\text{-}off}/\sigma_{\rm geom} \sim 6.0 \times 10^{-7}$. This suggests that the instantaneous overlap of the wave function of the o-Ps positron and that of the taregets' electrons which are in a spin-singlet state relative to the positron does not vary much among those atoms and molecules. The small value of $\sigma_{\rm pick\text{-}off}/\sigma_{\rm geom}$ indicates that o-Ps pick-off quenching occurs in ~ 1.7 millions collisions on average.

Conclusion

The experimental values of ${}^1Z_{\rm eff}$ are roughly proportional to the geometric collisional cross-section. This suggests that the pick-off quenching probabilities per collision for the o-Ps with atoms and molecules are almost constant.

The ratio of the cross-section for the pick-off annihilation to the collisional cross-section is [12]

$$\sigma_{\rm pick\text{-}off}/\sigma_{\rm geom} \sim 6.0 \times 10^{-7}\,. \qquad (5)$$

References

[1] G. F. Gribakin, et al., Rev. Mod. Phys. **82**, 2557 (2010).
[2] K. Iwata, et al., Phys. Rev. A **61**, 022719 (2000).
[3] S. Y. Chuang and S. J. Tao, Phys. Rev. A **9**, 989 (1974).
[4] M. Charlton, Rep. Prog. Phys. **48**, 737 (1985).
[5] M. Kakimoto, et al., J. Phys. B: At. Mol. Opt. Phys. **23**, (1990).
[6] K. Wada, et al, Phys. Rev. A **81**, 062710 (2010).
[7] H. Saito and T. Hyodo, Phys. Rev. Lett. **97**, 253402 (2006).
[8] J. Mitroy and I. A. Ivanov, Phys. Rev. A **65**, 012509 (2001).
[9] J. Mitroy and M. W. J. Bromley, Phys. Rev. A **67**, 034502 (2003).
[10] N. Shinohara, et al., Phys. Rev. A **64**, 062402 (2001).
[11] J. Y. Zhang and J. Mitroy, Phys. Rev. A **78**, 012703 (2008).
[12] K. Wada, et al., Eur. Phys. J. D, in press.